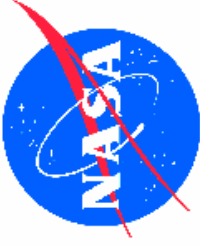


# **Evaluation of Erosion Resistance of Advanced Turbine Thermal Barrier Coatings**

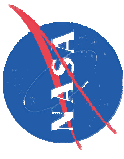
**Dongming Zhu, Maria A. Kuczmarski, Robert A. Miller,  
and Michael D. Cuy**



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Materials and Structures Division  
**NASA John H. Glenn Research Center  
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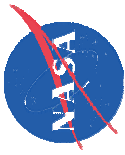
**This work was supported by NASA UEET and Fundamental Aeronautics Programs**

The 31st International Cocoa Beach Conference & Exposition on Advanced Ceramics & Composites  
Daytona Beach, Florida, January 22-26, 2007



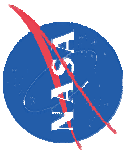
## Abstract

**The erosion resistant turbine thermal barrier coating system is critical to aircraft engine performance and durability. By demonstrating advanced turbine material testing capabilities, we will be able to facilitate the critical turbine coating and subcomponent development and help establish advanced erosion-resistant turbine airfoil thermal barrier coatings design tools. The objective of this work is to determine erosion resistance of advanced thermal barrier coating systems under simulated engine erosion and/or thermal gradient environments, validating advanced turbine airfoil thermal barrier coating systems based on nano-tetragonal phase toughening design approaches.**



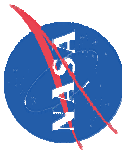
## Outline

- OBJECTIVE: Develop advanced thermal barrier coating systems with superior erosion resistance in engine erosion and thermal gradient environments, and establish coating performance models**
- High-heat-flux erosion test capability development
  - Advanced low conductivity and erosion-resistant thermal barrier coatings performance evaluation
  - Determine erosion resistance of advanced low conductivity thermal barrier coating systems under simulated engine erosion and high-heat-flux thermal gradient environments
  - Erosion and impact mechanisms
  - Summary and future directions



## Advanced Low Conductivity Thermal Barrier Coating Development Requirements

- Low conductivity (“1/2” of the baseline) retained under thermal gradient at 2400°F
- Improved sintering resistance and phase stability (up to 3000°F)
- Excellent durability and mechanical properties
  - Cyclic life
  - Toughness
  - Erosion/impact resistance
  - CMAS and corrosion resistance
  - Compatibility with the substrate/TGO
- Processing capability using existing infrastructure and alternative systems
- Other design considerations
  - Favorable optical properties
  - Potentially suitable for various metal and ceramic components



## Development of Advanced Defect Cluster Low Conductivity Thermal Barrier Coatings

- Multi-component oxide defect clustering approach (Zhu and Miller, *US Patents No. 6,812,176 and No.7,001,859; US patent application 11/510,574*)

e.g.:  $\text{ZrO}_2\text{-Y}_2\text{O}_3\text{-Nd}_2\text{O}_3(\text{Gd}_2\text{O}_3, \text{Sm}_2\text{O}_3)\text{-Yb}_2\text{O}_3(\text{Sc}_2\text{O}_3)$  – **TT systems**



Primary stabilizer



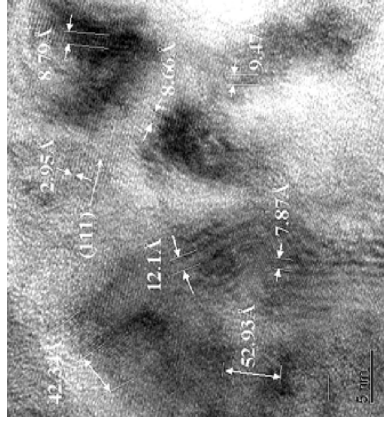
Oxide cluster dopants with distinctive ionic sizes



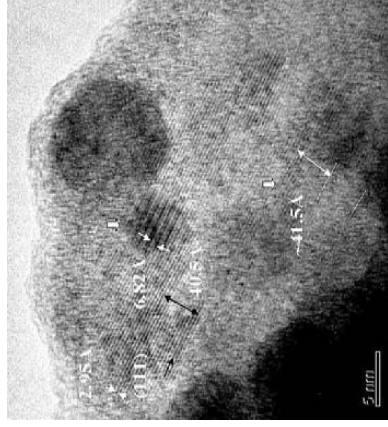
Toughening dopants

- Defect clusters associated with dopant segregation

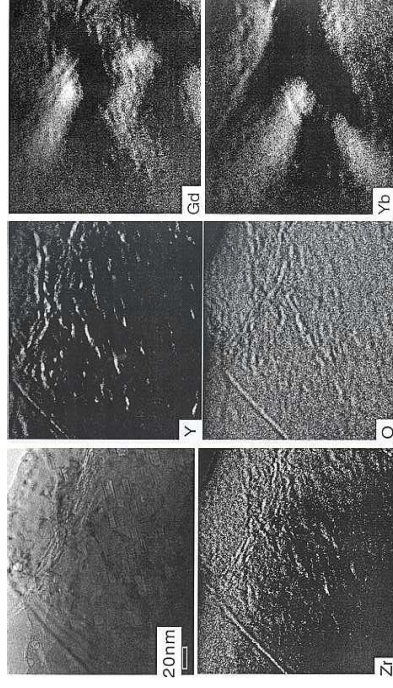
- A new six-component, high toughness coatings also developed (patent pending)



Plasma-sprayed  $\text{ZrO}_2\text{-13.5mol\%(Y, Nd, Yb)}_2\text{O}_3$



EB-PVD  $\text{ZrO}_2\text{-12mol\%(Y, Nd, Yb)}_2\text{O}_3$



EELS elemental maps of  $\text{EB-PVD ZrO}_2\text{-14mol\%(Y, Gd, Yb)}_2\text{O}_3$

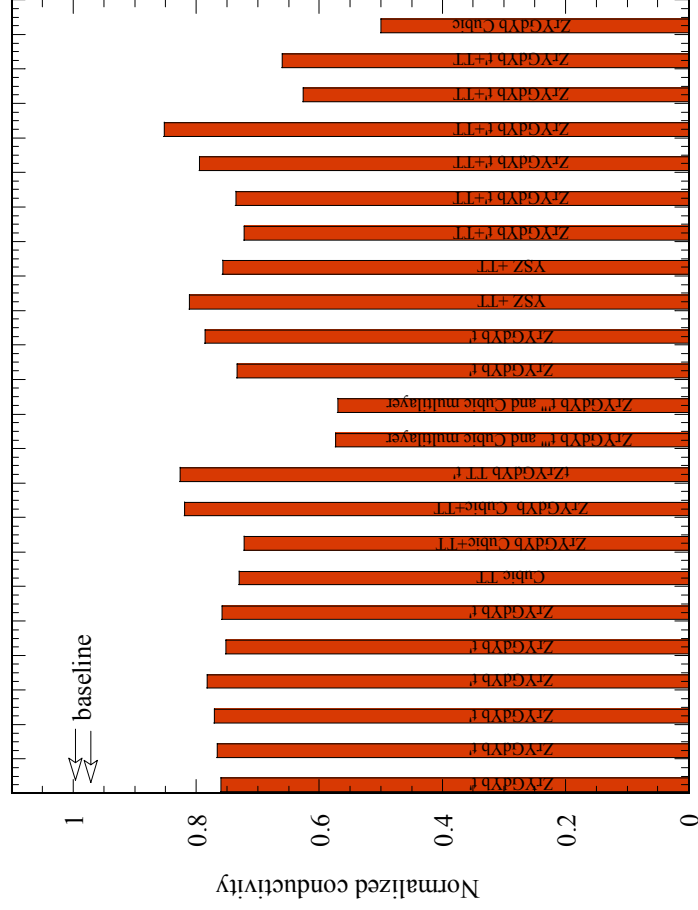
## Thermal Conductivity and Cyclic Durability Evaluations

- **A new series of EB-PVD  $\text{ZrO}_2\text{-Y}_2\text{O}_3\text{-Gd}_2\text{O}_3\text{-Yb}_2\text{O}_3$  and  $\text{ZrO}_2\text{-Y}_2\text{O}_3\text{-Gd}_2\text{O}_3\text{-Yb}_2\text{O}_3\text{-TT}$  coatings designed for improved toughness and erosion resistance**
- **Thermal conductivity and cyclic durability characterized**

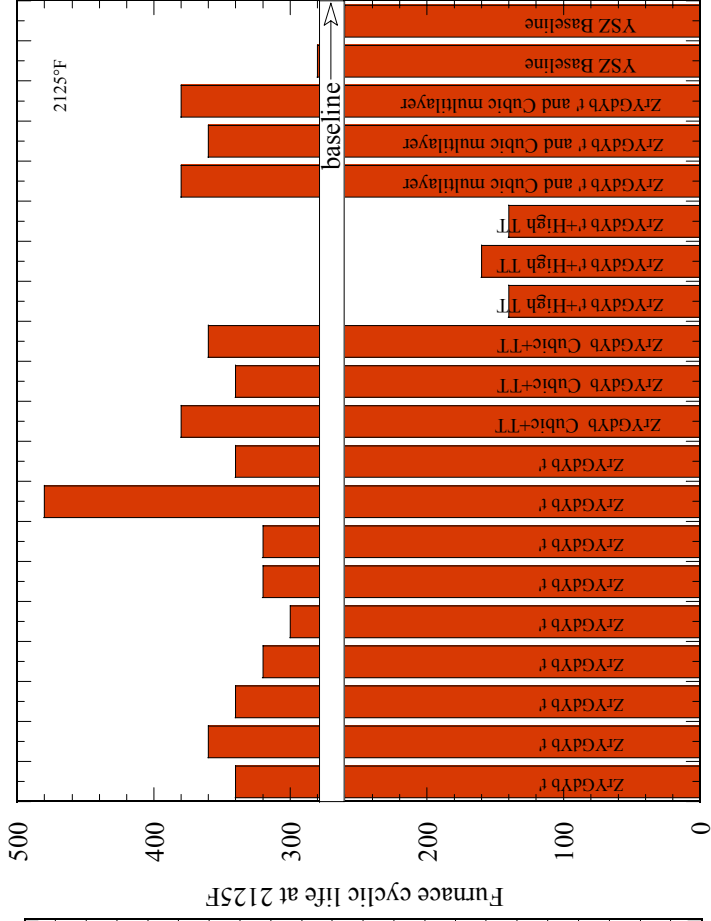


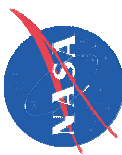
## Selected coating specimen configurations

## Thermal conductivity of EB-PVD erosion TBCs



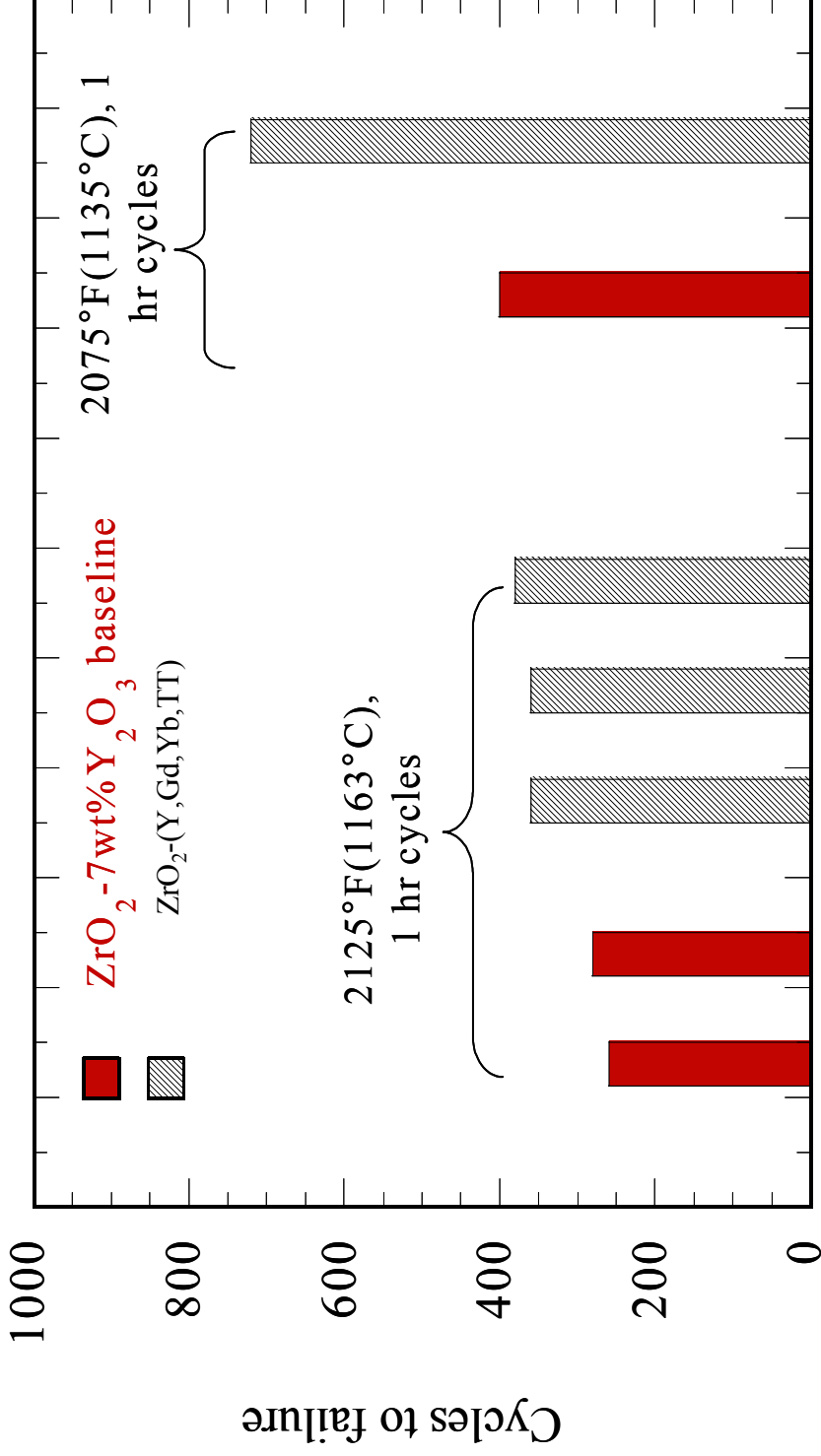
## Furnace cyclic life of EB-PVD erosion coatings



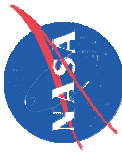


## Thermal Conductivity and Cyclic Durability Evaluations (continued)

### — Effect of temperature on coating cyclic life

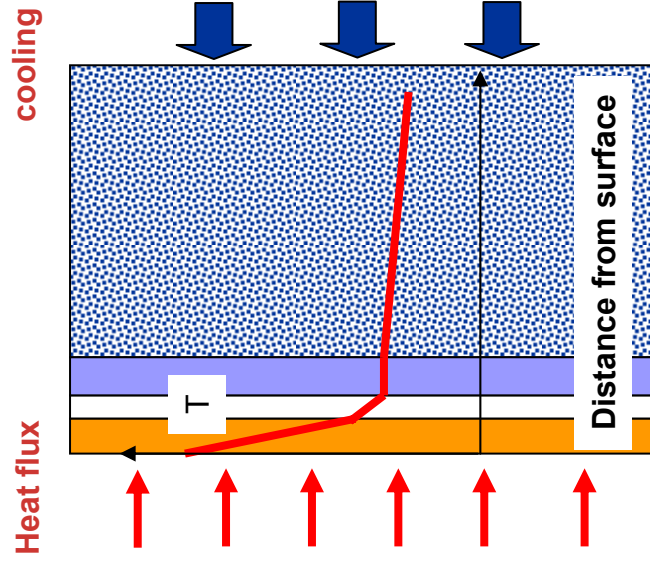


Coating Type



## High-Heat-Flux Test Approaches

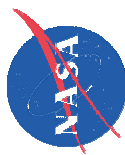
- High-heat-flux laser tests for thermal barrier coating development
- Temperature gradient requirements: 20-200°F/mil for typical 5-15 mil thick coatings



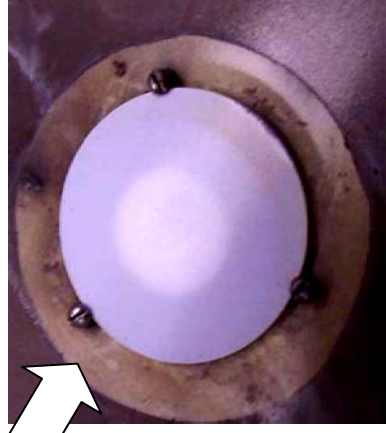
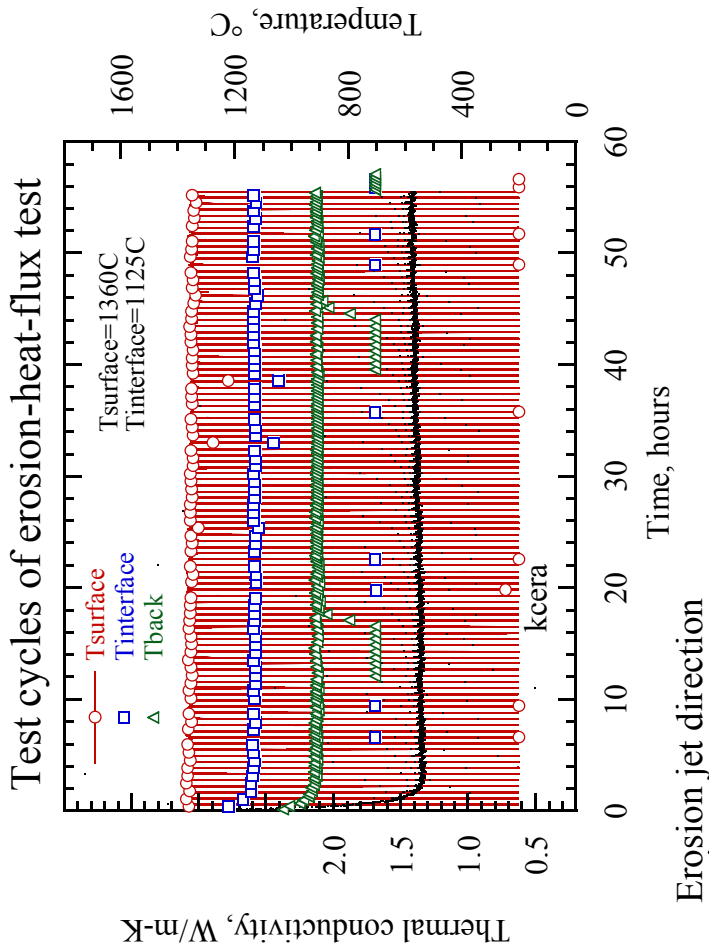
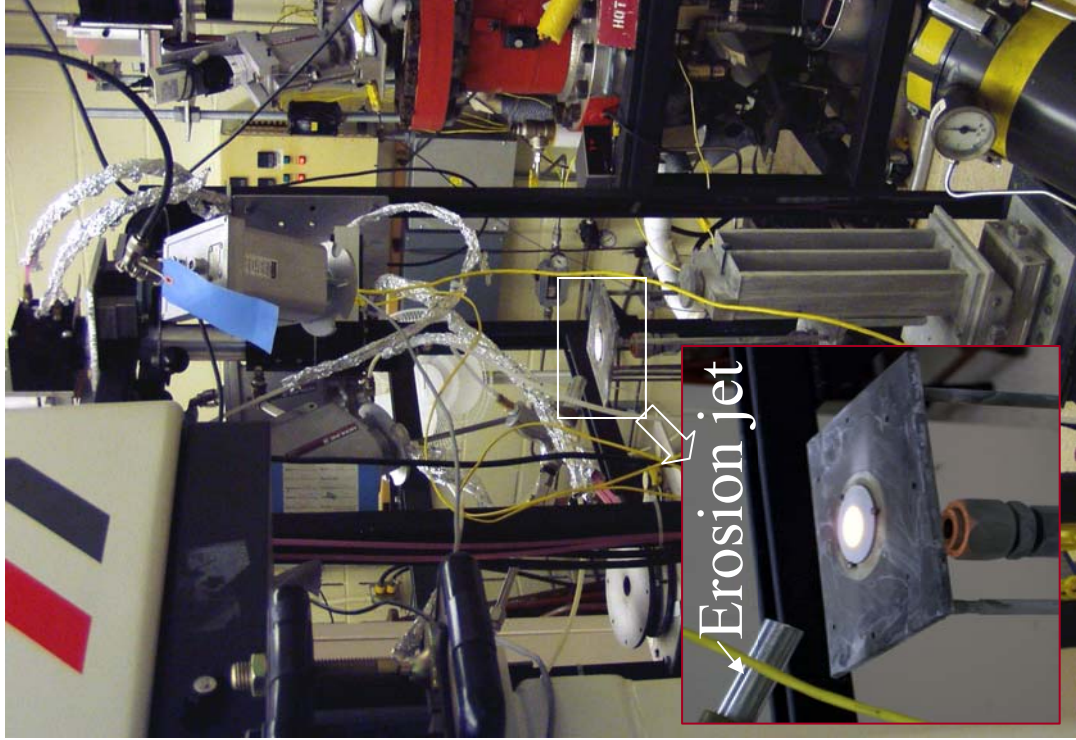
NASA CO<sub>2</sub> Laser Rig

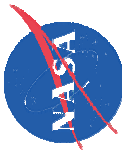


Current capability up to 315 W/cm<sup>2</sup> for TBCs



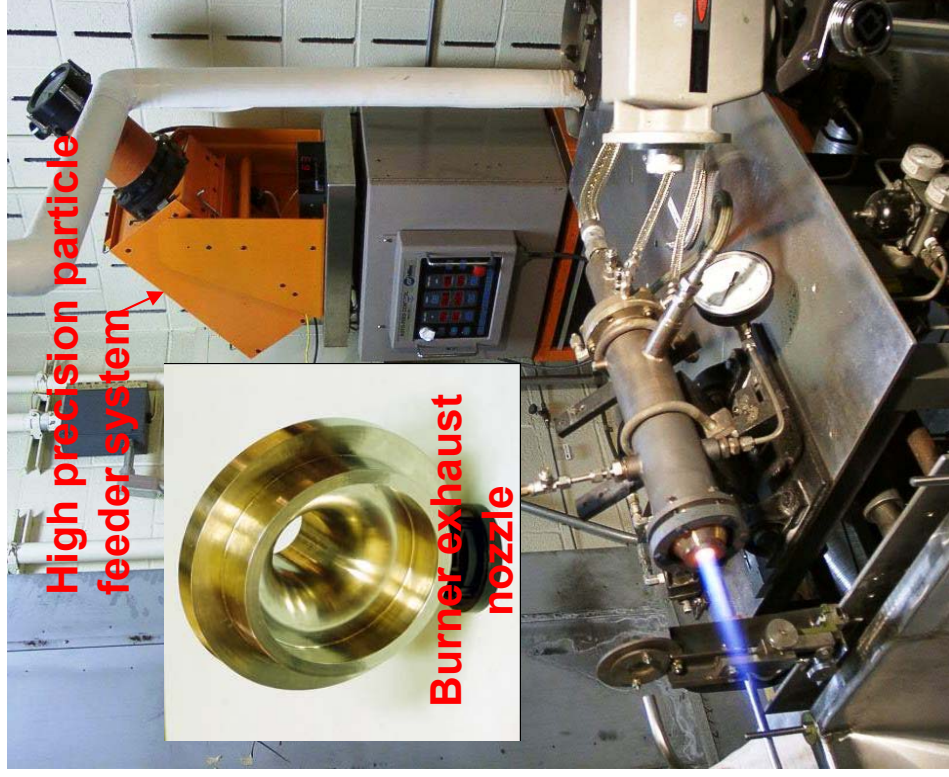
# Laser High-Heat-Flux Erosion Test Rig

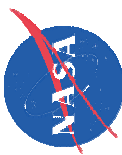




## Mach 0.3-1.0 High Velocity Burner Erosion Test Rig

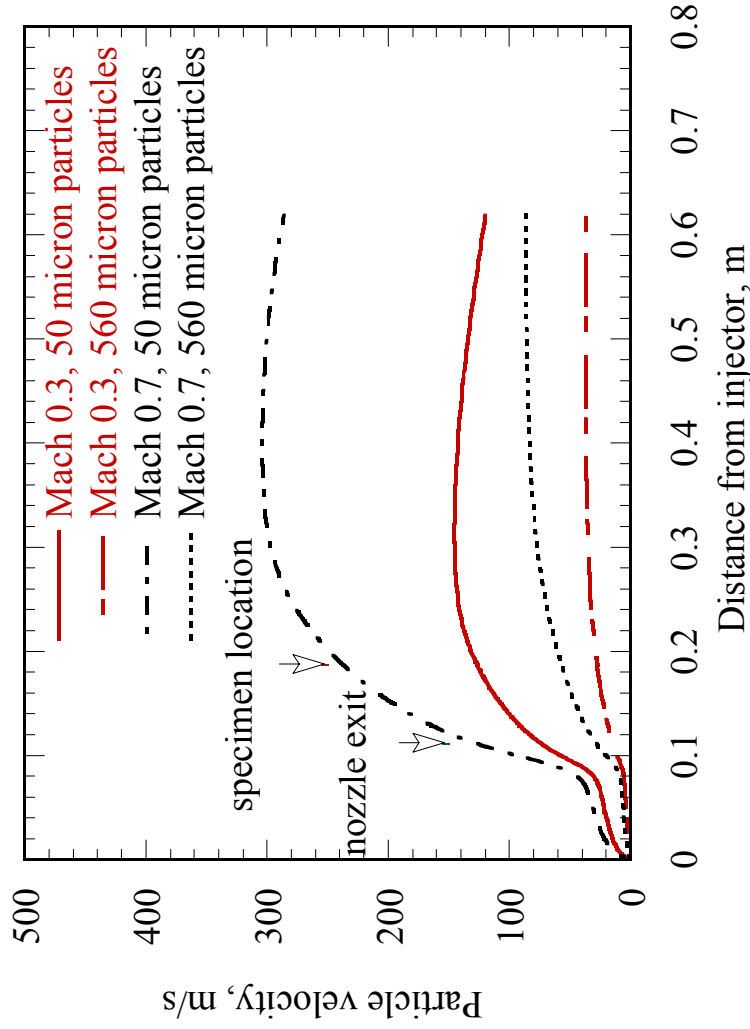
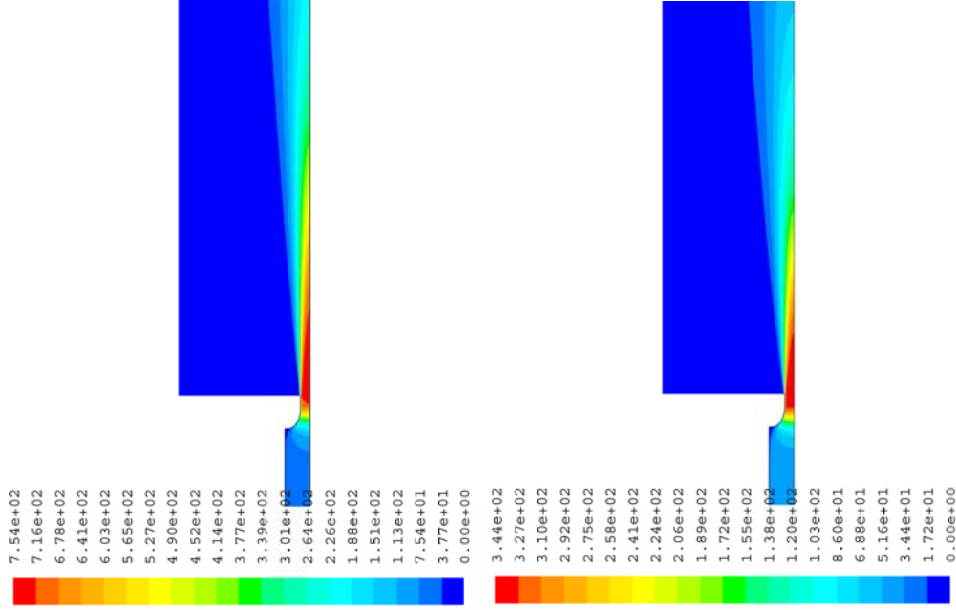
- Burner erosion rig was developed using a newly designed exhaust nozzle and by accommodating increased burner gas flow to achieve higher-heat fluxes with flame stability and uniformity

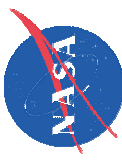




# CFD Modling of the High Velocity Burner Erosion Rig using Fluent Codes

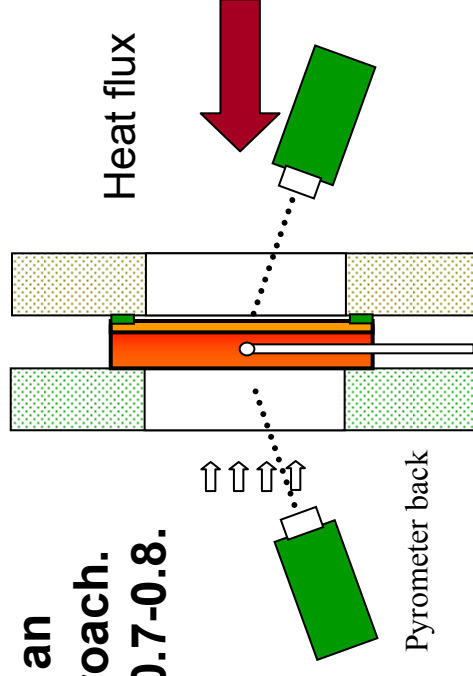
- Computational Fluid Dynamics (CFD) modeling of burner flow and particle velocities providing vital erosion test information





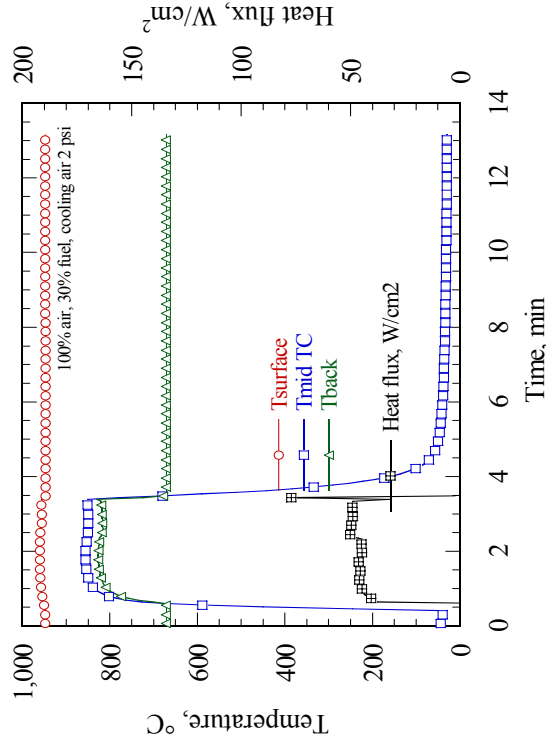
## Burner Erosion Rig Heat Flux Characterizations

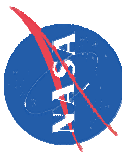
- Burner rig heat fluxes characterized using an embedded thermocouple (TC) sensor approach.
- A heat flux of 50 W/cm<sup>2</sup> achieved at Mach 0.7-0.8.



### TC

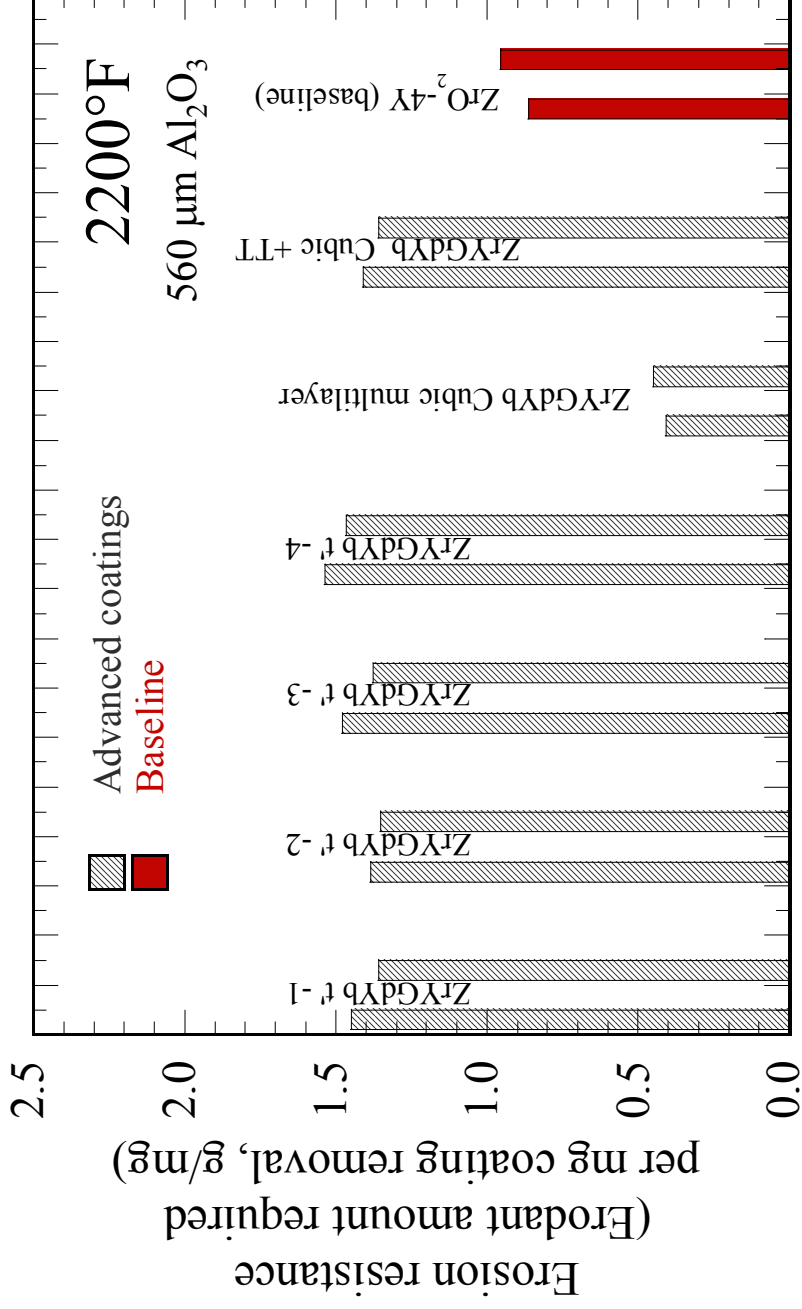
Heat flux matrix Data 7

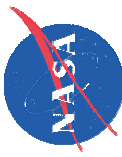




## Erosion Resistance of Advanced Multicomponent Low Conductivity Thermal Barrier Coatings

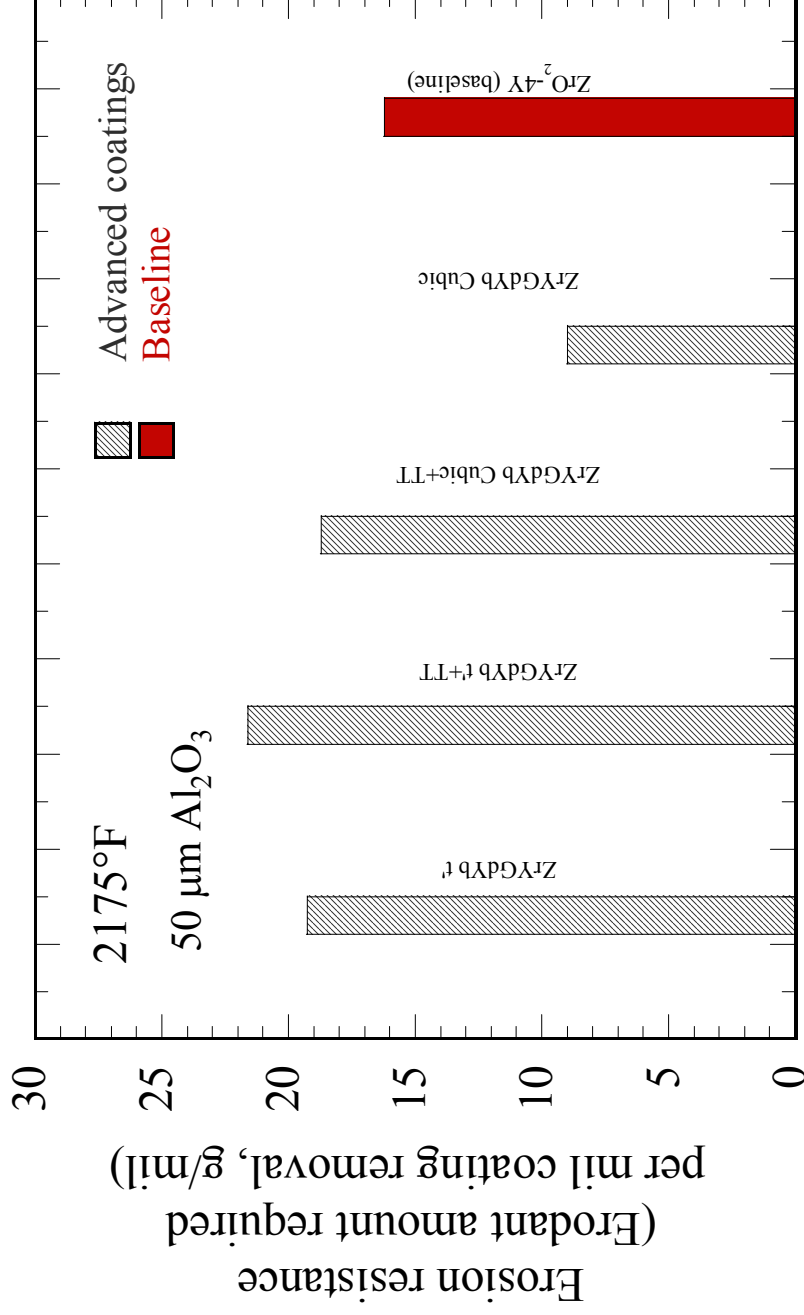
- Improved impact/erosion resistance observed for advanced low conductivity six-component coatings

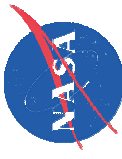




## Advanced Multicomponent Low Conductivity Thermal Barrier Coatings

- Improved erosion resistance demonstrated for advanced low conductivity thermal barrier coatings

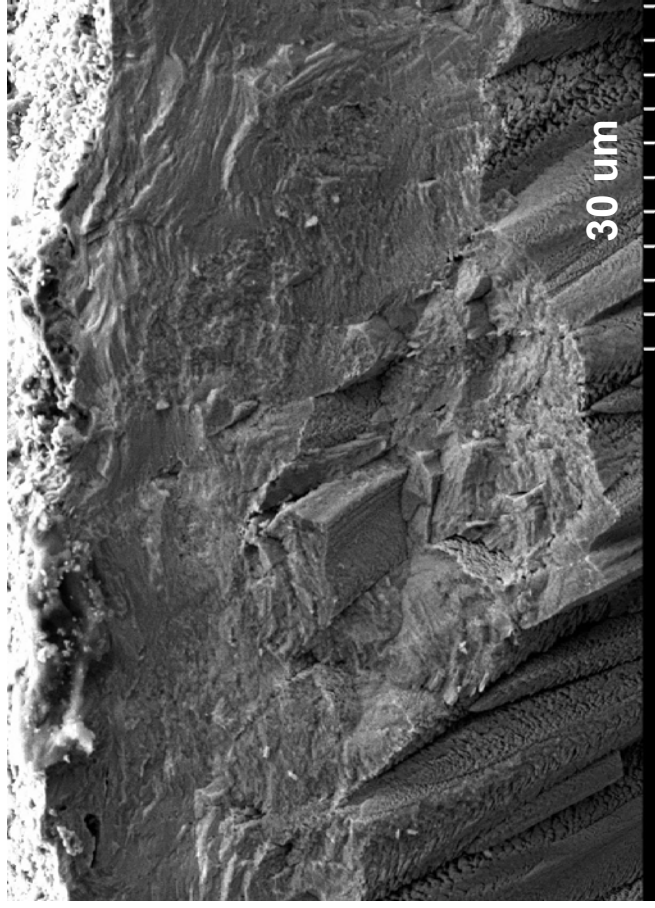




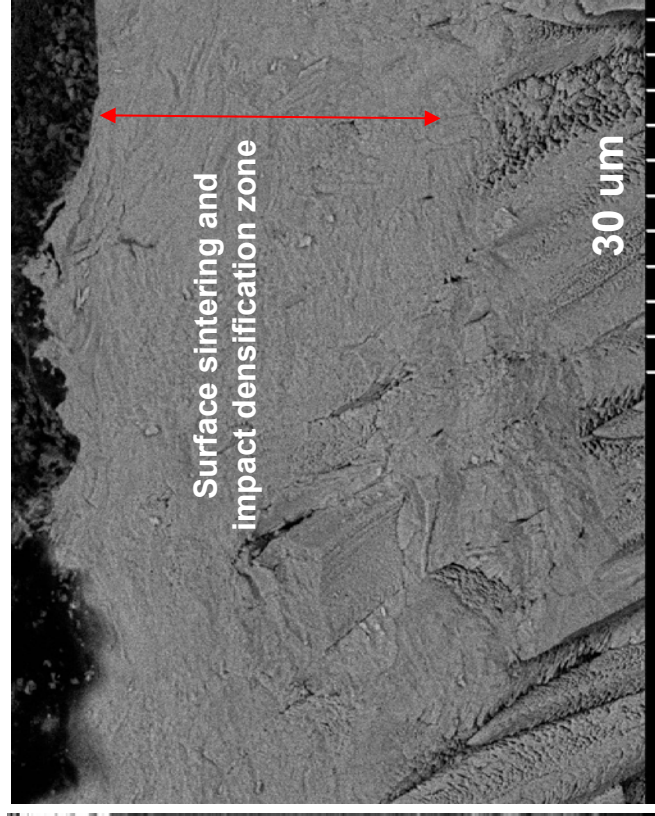
## Erosion/Impact Failure Mechanisms of Thermal Barrier Coatings

- Surface sintering and impact densification zones observed, with subsequent spallation under the erodant further impact

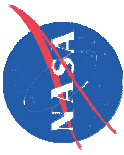
**SEM micrographs of advanced thermal barrier coating after impact/erosion damage**



**Secondary electron image**



**Backscattered electron image**



## Summary

- **High heat-flux and simulated engine erosion tests established for advanced thermal barrier coatings development**
- **Low conductivity and erosion resistant thermal barrier coatings developed based on nano-tetragonal phase toughening design approaches**
  - The optimized coatings demonstrated excellent conductivity benefit and improved erosion resistant capability
- **Completed initial simulated engine erosion testing for validating coating performance models**
  - Completed 600 hr cyclic durability tests at 2075°F and 50 hrs combined laser erosion-high heat flux tests at 2350°F for down-selected turbine airfoil coating systems
- **Demonstrated the coating systems in the Mach 0.3-1 burner erosion rig under simulated turbine engine and erosion environments**